Enabling Spaceflight using Metal Additive Manufacturing

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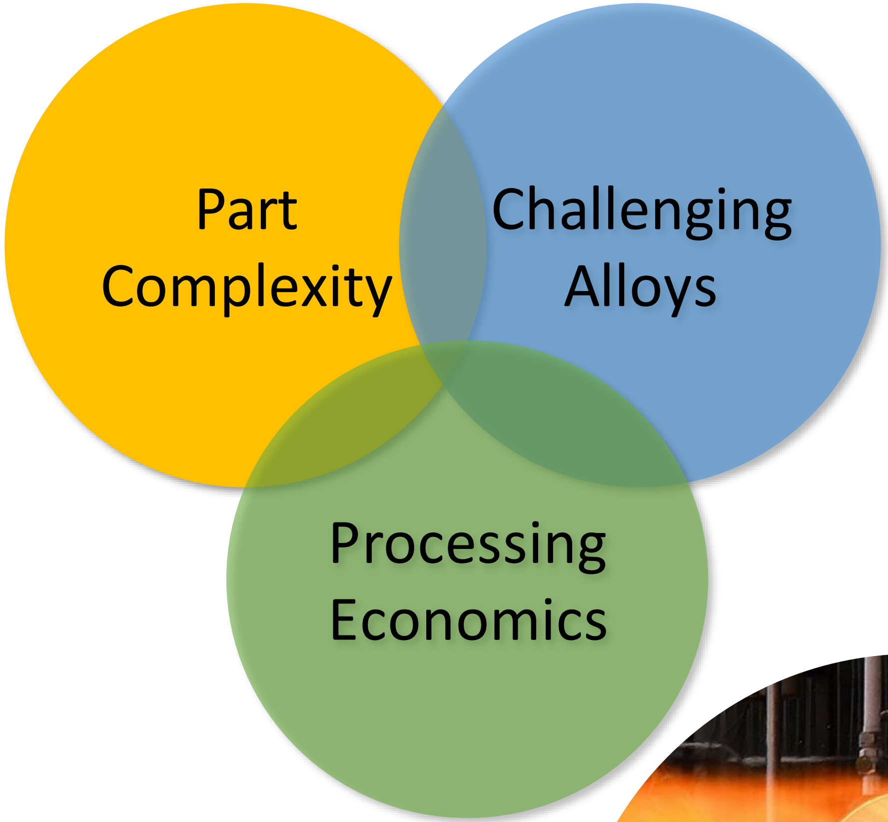
The Case for Additive Manufacturing in Propulsion

- Metal Additive Manufacturing (AM) provides significant advantages for lead time and cost over traditional manufacturing for rocket engines
    - Lead times reduced by 2-10x
    - Cost reduced by more than 50%
- Complexity is inherent in liquid rocket engines and AM provides new design and performance opportunities
- Materials that are difficult to process using traditional techniques, long-lead, or not previously possible are now accessible using metal additive manufacturing

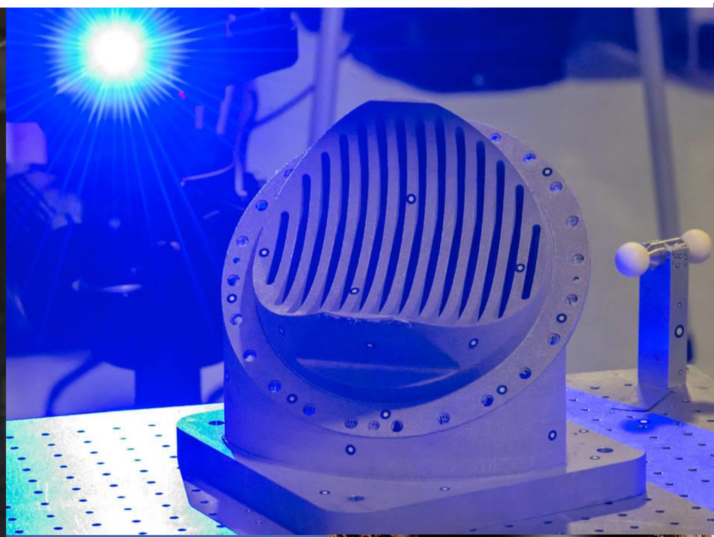


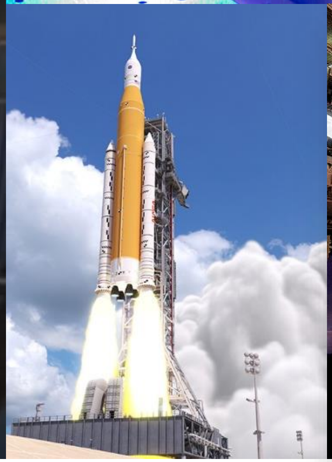
Case Study for AM

Category	Traditional Manufacturing	Initial AM Development	Evolving AM Development
Design and Manufacturing Approach	Multiple forgings, machining, slotting, and joining operations to complete a final multi-alloy chamber assembly	Four-piece assembly using multiple AM processes; limited by AM machine size. Two-piece L-PBF GRCop-84 liner and EBW-DED Inconel 625 jacket	Three-piece assembly with AM machine size restrictions reduced and industrialized. Multi-alloy processing; one-piece L-PBF GRCop-42 liner and **Inconel 625 LP-DED jacket**
Schedule (Reduction)	18 months	8 months (56%)	5 months (72%)
Cost (Reduction)	$310,000	$200,000 (35%)	$125,000 (60%)

As AM process technologies evolve using multi-materials and processes, additional design and programmatic advantages are being discovered

Additive Manufacturing in use on NASA Space Launch System (SLS)

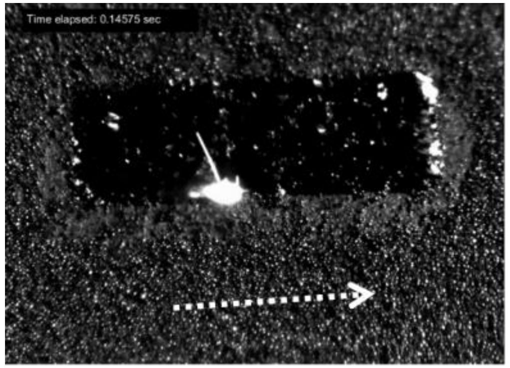




Successful hot-fire testing of full-scale additive manufacturing (AM) Part to be flown on SLS RS-25
RS-25 Pogo Z-Baffle – Used existing design with AM to reduce complexity from <u>127 welds to 4 welds</u>

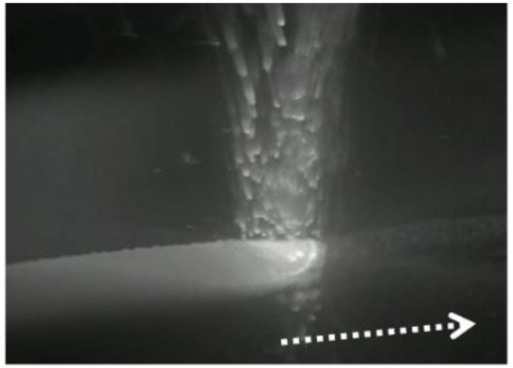
Ref: Andy Hardin, Steve Wofford/ NASA MSFC

AM Processes for various applications

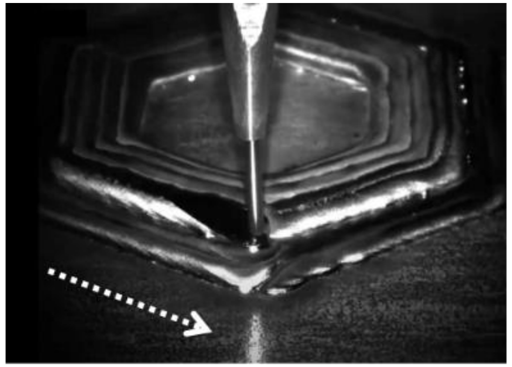


Laser Powder Bed Fusion

Electron Beam Powder Bed Fusion

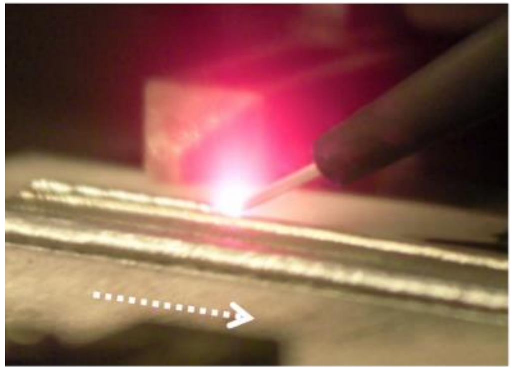


Laser Powder DED

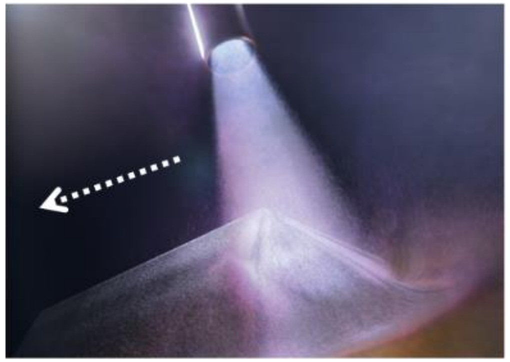


Laser Wire DED

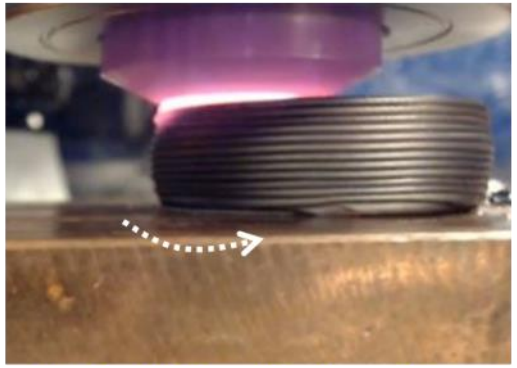
Arc Wire DED



Electron Beam Wire DED



Cold Spray



Additive Friction Stir Deposition

Ultrasonic Additive Manufacturing

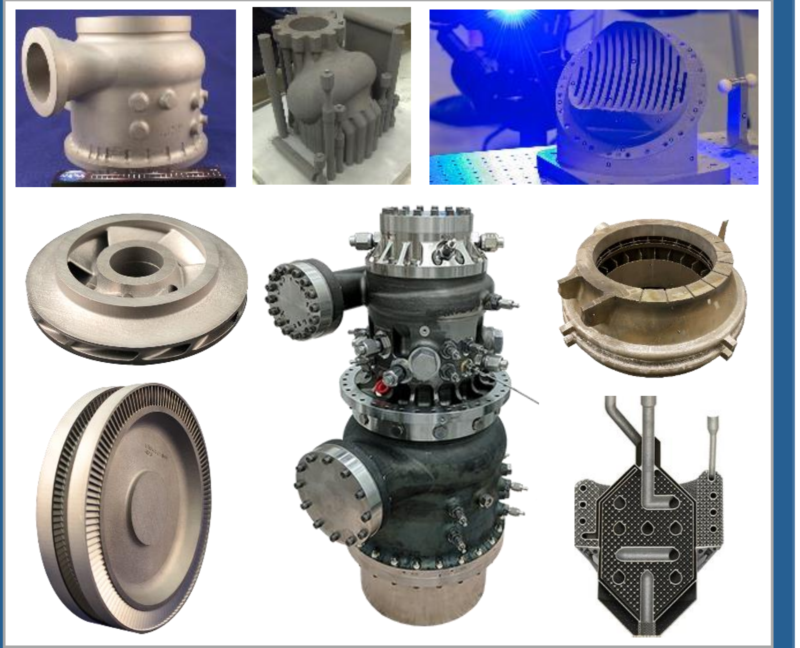
A) Laser Powder Bed Fusion [https://doi.org/10.1016/j.actamat.2017.09.051], B) Electron Beam Powder Bed Fusion *[Credit: Courtesy of Freemelt AB, Sweden]*, C) Laser Powder DED *[Credit: Formalloy]*, D) Laser Wire DED *[Credit: Ramlab and Cavitar]*, E) Arc Wire DED *[Credit: Institut Maupertuis and Cavitar]*, F) Electron Beam DED *[NASA]*, G) Cold spray *[Credit: LLNL]*, H) Additive Friction Stir Deposition [NASA], I) Ultrasonic AM *[Credit: Fabrisonic]*.

Reference: Gradl, P., Tinker, D., Park, A., Mireles, P., Garcia, M., Wilkerson, R., Mckinney, C. (2022). "Robust Metal Additive Manufacturing Process Selection and Development for Aerospace Components". Journal of Material Engineering and Performance (JMEP). Article in Review.

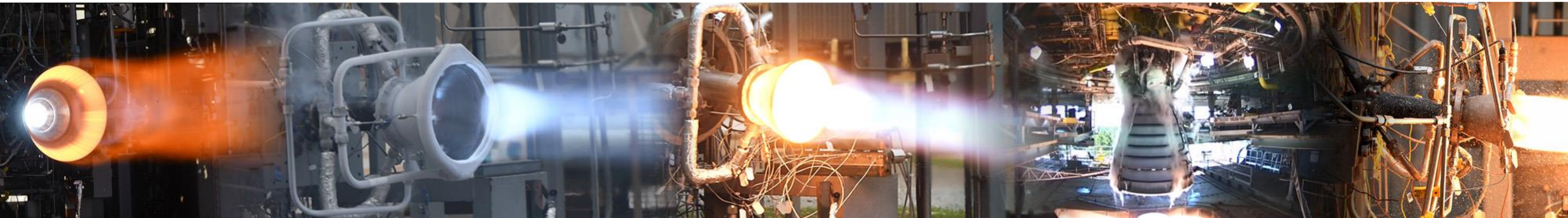
Additive Manufacturing (AM) Development at NASA for Liquid Rocket Engines

Laser Powder Bed Fusion (L-PBF) Copper Alloys combined with other AM processes to provide bimetallic

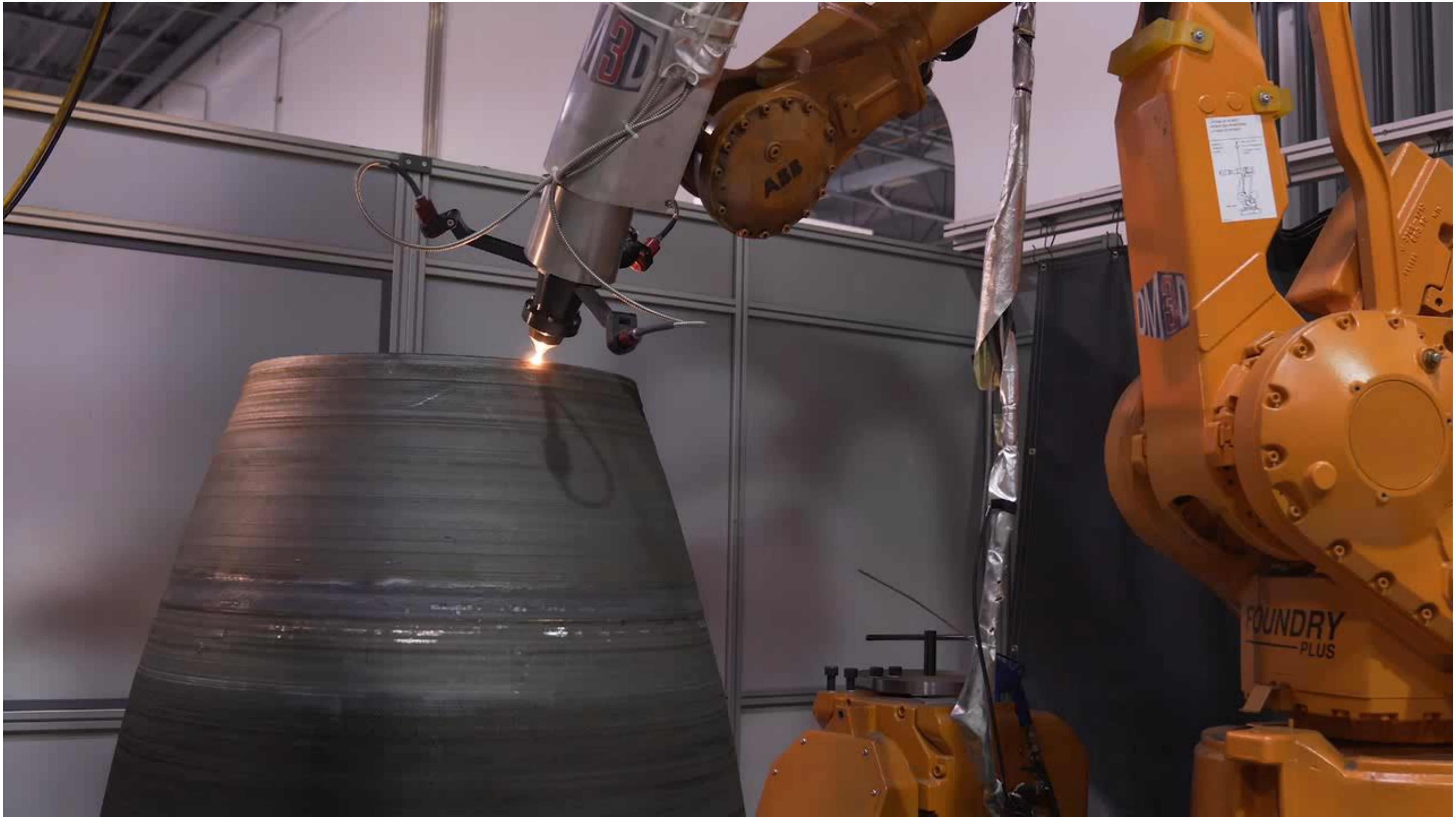
Directed Energy Deposition



L-PBF of complex components, new alloy developments for harsh environment



Laser Powder Directed Energy Deposition (DED)



Laser Powder Directed Energy Deposition (LP-DED) Large Scale Nozzles

60” (1.52 m) diameter and 70” (1.78 m) height with integral channels
90 day deposition

95” (2.41 m) dia and 111” (2.82 m) height
Near Net Shape Forging Replacement

Reference: P.R. Gradl, T.W. Teasley, C.S. Protz, C. Katsarelis, P. Chen, Process Development and Hot-fire Testing of Additively Manufactured NASA HR-1 for Liquid Rocket Engine Applications, in: AIAA Propuls. Energy 2021, 2021: pp. 1–23. https://doi.org/10.2514/6.2021-3236.

Additive Manufacturing Typical Process Flow

Process Parameters

AM Design and Pre-Processing
- Part Design
- Analysis
- Model Check
- Build Layout
- Support Generation
- Model Slicing
- Toolpath

Additive Manufacturing Process

Metal Feedstock

Post-Processing
- Powder Removal
- Heat Treatments
- Support Removal
- Build Plate Removal
- Inspections
- Final Machining
- Welding / Brazing
- Polishing
- Cleaning

Part in Service
- Assembly
- Validation / Testing
- Qualified Metallurgy
- Part Production Plan

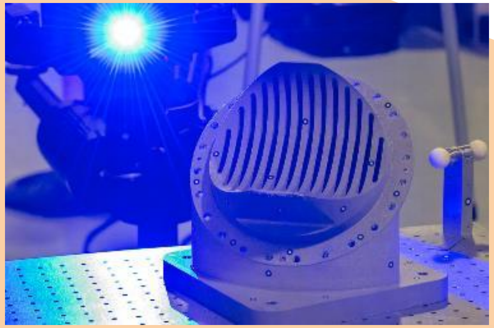
Qualification

Proper AM process selection requires an integrated evaluation of all process lifecycle steps

Emerging Areas of Development

- Maturing each of the AM processes and understanding of microstructure, properties, build limitations, and methods for design and post-processing.
- Ongoing development for large scale AM using DED and other processes.
- Continuous hot-fire and component testing to advance various combustion chambers, injectors, nozzles, ignition systems, turbomachinery, valves, lines, ducts, in-space thrusters.
- Polishing (surface enhancements internally) and post-processing development.
- Combining various AM processes for multi-alloy solutions or additional design options.
- Advancement of commercial supply chain for unique alloys (GRCop-42, NASA HR-1, JBK-75).
- New alloy development (Refractory, Ox-rich environments, AM-specific alloys).
- Material databases of metal AM properties to allow for conceptual design – tensile, fatigue, and thermophysical.
- Design complexity using lattices, topology optimization, generative design, and thin-wall structures.
- Standards and certification of metal AM are evolving for human spaceflight.

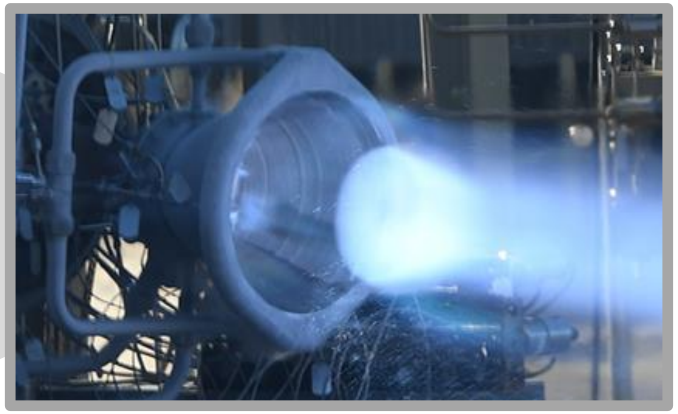
Industrial Maturity and TRL of AM Processes



L-PBF

Cold spray

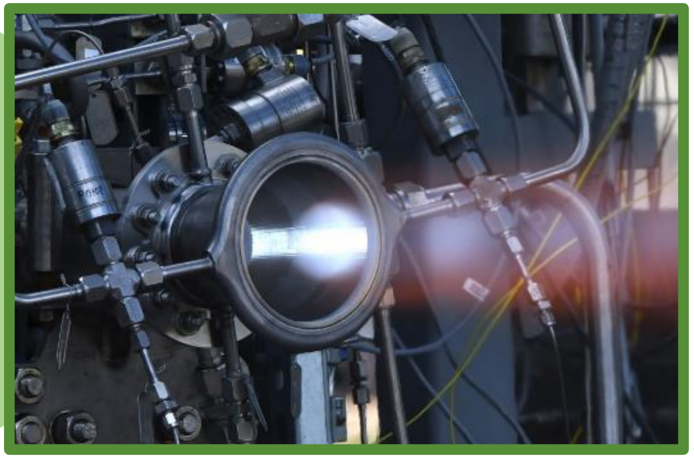
LP-DED



L-PBF

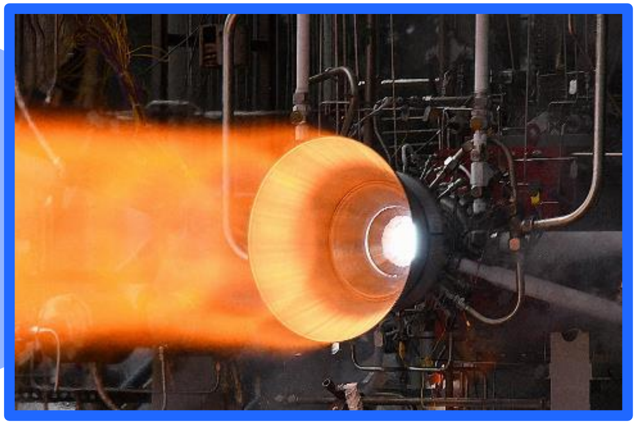
AW-DED

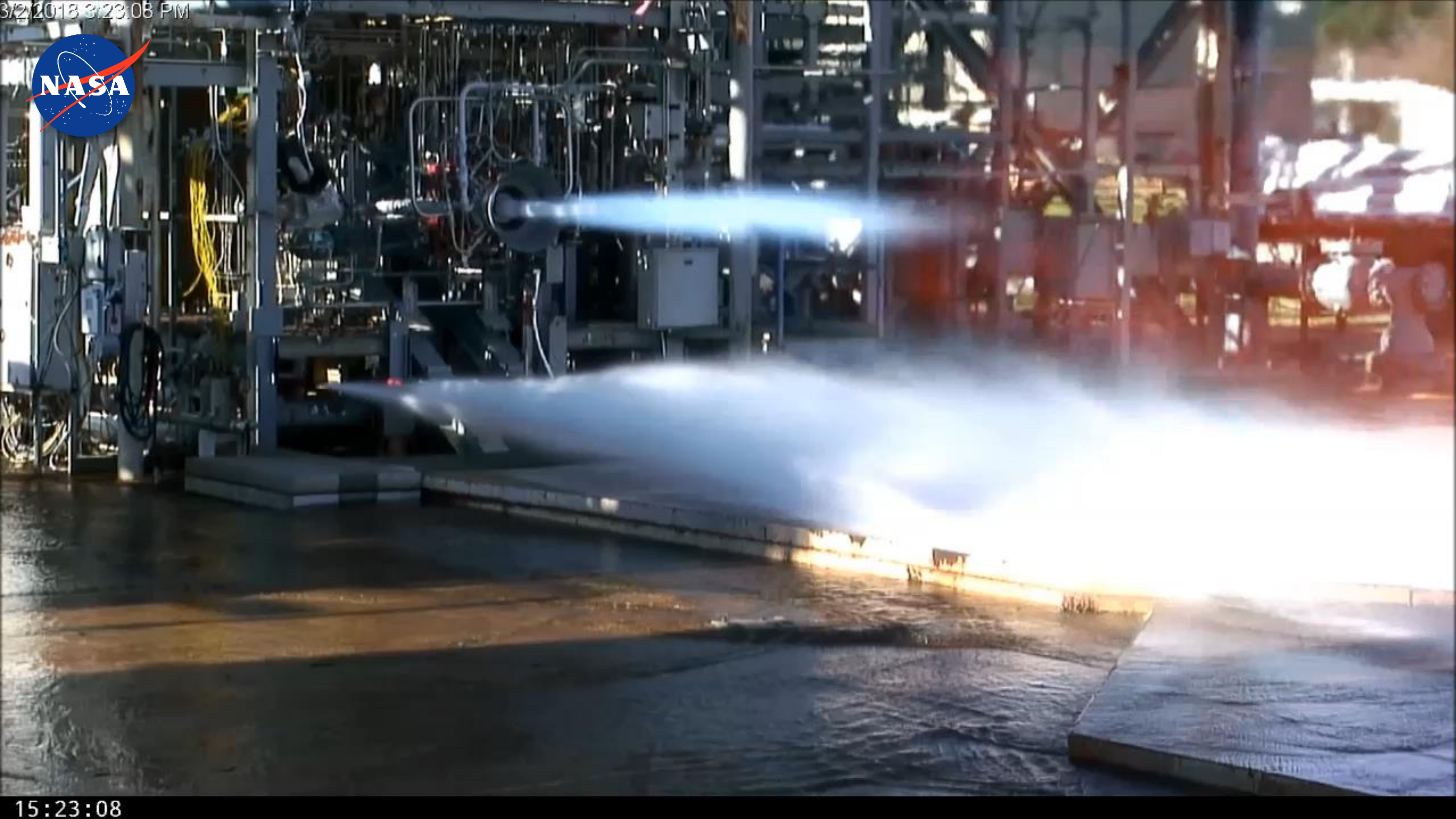
LW-DED



L-PBF

EBW-DED

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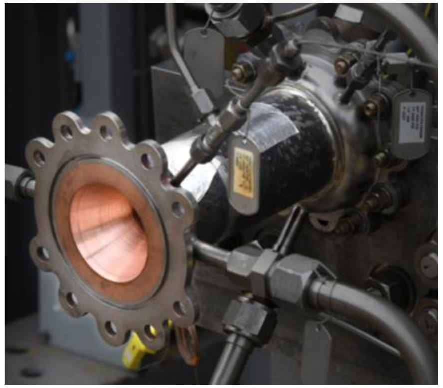
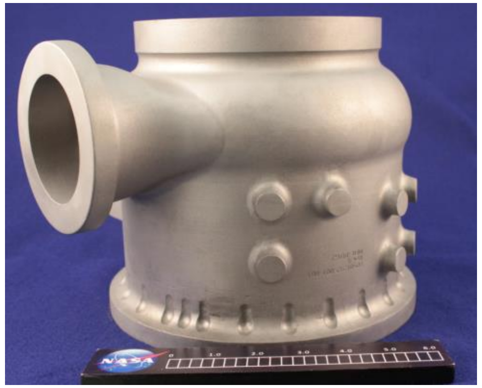
General Summary

- It's *all* welding, so same physics apply
- Additive manufacturing is <u>not a solve-all</u>; consider trading with other manufacturing technologies and use <u>only</u> when it makes sense
- Complete understanding of design process, build-process, and post-processing critical to take full advantage of AM
- Various processes exist each with unique advantages and disadvantages
- Additive manufacturing takes practice!
- Standards and certification of the processes in-work
- AM is evolving and there is a lot of work ahead





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